Time Switching for Wireless Communications with Full-Duplex Relaying in Imperfect CSI Condition

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Abstract

In this paper, we consider an amplify-and-forward (AF) full-duplex relay network (FDRN) using simultaneous wireless information and power transfer, where a battery-free relay node harvests energy from the received radio frequency (RF) signals from a source node and uses the harvested energy to forward the source information to destination node. The time-switching relaying (TSR) protocol is studied, with the assumption that the channel state information (CSI) at the relay node is imperfect. We deliver a rigorous analysis of the outage probability of the proposed system. Based on the outage probability expressions, the optimal time switching factor are obtained via the numerical search method. The simulation and numerical results provide practical insights into the effect of various system parameters, such as the time switching factor, the noise power, the energy harvesting efficiency, and the channel estimation error on the performance of this network. It is also observed that for the imperfect CSI case, the proposed scheme still can provide acceptable outage performance given that the channel estimation error is bounded in a permissible interval.

Keywords: energy harvesting, SWIPT, full-duplex relaying, imperfect CSI.

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1. Introduction

Conventionally, wireless devices are powered by batteries, which have a limited operational lifetime, and have to be replaced or recharged periodically to maintain the network connectivity. In practice, this could be costly, inconvenient, and even infeasible. To overcome the above limitation, there have been several research ideas on microwave-enable wireless energy transfer (WET), where energy is continuously and stabily supplied over the air. More advancingly, the WET technologies to power the devices efficiently open up the potential to build a fully wireless powered communication network (WPCN), in which wireless devices communicate using only the power harvested by means of WET [1].

Relaying is an effective way to combat the performance degradation caused by fading, shadowing, and path loss. In relay networks, the relay nodes help to boost the information exchange between source nodes and destination nodes, by forwarding (with or without decoding) the information-bearing radio frequency signals from sources to destinations. Because of the important role of relays, there have been numerous attempts to improve the efficiency of energy using at the relay. For instance, the authors in [2] proposed a holistic power model equipped with an iterative antenna selection for decode-and-forward (DF) MIMO relay systems. With the optimal active relay subsets selected by the proposed algorithm, it has a remarkable benefit in terms of power consumption over conventional DF MIMO relay systems. However, a more natural idea is to apply WET technologies to relay networks. Simultaneous wireless information and power transfer (SWIPT) is a kind of communications where relay nodes can be powered by energy harvested from the source RF signals. This interesting idea has been presented firstly in the pioneering works by Varshney [3] and Grover [4]. Later, time-switching and power-splitting have been introduced in [5] as two practical architectures for SWIPT in relay networks. The drawback of that paper is that the authors only shown a performance bound that in general cannot be achieved by practical receivers.

Since then, RF energy harvesting and information transfer via relays have also drawn significant attention. The throughput performance of amplify-and-forward (AF) and decode-and-forward (DF) relaying systems for both time-switching (TSR) and power-splitting (PSR) protocols was studied rigorously in [6] and [7]. In these papers, Nasir et al. have provided practical insights into the effect of various system parameters, such as energy harvesting time, power splitting ratio, source transmission rate, source-to-relay distance, noise power, and energy harvesting efficiency, on the performance of wireless energy harvesting and information processing using either AF or DF relay nodes. It’s interested to learn that for AF relaying scheme, TSR protocol outperforms PSR protocol on throughput performance at low SNR regime, while for DF relaying scheme, PSR is better than TSR for a wide range of SNRs. More advanced results to improve the performance of energy harvesting in cooperative networks were found in [8], [9]. In [8], a network with multiple source-destination pairs communicated with each other via energy harvested relays is considered, in which harvested energy is distributed properly among the relays to obtain better performance. The main concentration of [9] is on the strategies to select the energy-harvested relays which are randomly located in the network. Nevertheless, all the above works are limited on half-duplex (HD) relaying mechanism only and do not mention the case that the channel state information (CSI) is not perfect.

The application of wireless information and power transfer to full-duplex relaying systems was first introduced in [10]. In that paper, the authors focused on a source-relay-destination dual-hop scenario where the relay is powered via RF energy harvesting, and derived throughput performance analysis of the system. More interestingly, Zeng [11] proposed a new protocol for energy harvesting with full-duplex relaying, where part of the energy (loop energy) that is used for information transmission by the relay can be harvested and reused in addition to the dedicated energy sent by the source. However, all of the above analysis were based on the assumption that the channel state information (CSI) is perfectly available at the relay and the destinations.

Indeed, there have also been several results on performance analysis of relay networks with imperfect CSI. Recently, the exact integral and approximate closed-form expression for the outage probability of two-way full-duplex relaying networks with residual loop interference and imperfect CSI has been derived in [12], but energy harvesting has not been deployed in this paper. Reversely, Li et al. [13] did take account of the imperfect CSI condition in a two-way AF relay systems with energy harvesting. Nonetheless, they only derived the maximum achievable sum rate, not the exact ergodic capacity of the system, and their results were limited at half-duplex model.

As of the authors' knowledge, no work has considered the impact of channel estimation error on the performance of full-duplex relaying networks that apply the RF energy harvesting idea.

In this paper, we focus on the throughput performance of wireless information and power transfer with full-duplex relaying in the condition of imperfect CSI at both relay and destination. Using the similar setup as [10], we consider a FD relaying system equipped with two separate antennas, one for information transmission and one for information reception.

Regarding the relaying and energy harvesting protocols, we focus on amplify-and-forward and time-switching relaying protocol. The optimal time-switching factor is found by Golden section search algorithm. The most significant contribution of this paper is to measure the effect of channel estimation error on the performance of energy-harvested full-duplex relaying systems, both by mathematical analysis and simulation.

The rest of the paper is organized as follows. The next section introduces the system model of full-duplex relay networks with SWIPT. Section 3 provides the detailed analysis of the throughput and outage performance of the system. Numerical results to confirm the mathematical analysis are presented in Section 4. Finally, Section 5 concludes the paper.

2. System Model

We consider a dual-hop FD relaying system illustrated in **Fig. 1**, where the source S sends information to the destination D with the help of an amplify-and-forward relay R. Assume that the direct connection between source and destination is weak, so the relay R is deployed to enhance this connection without having its own data to transmit. The relay is equipped with a transmit antenna and a receive antenna, which suffers from residual self-interference due to signal leakage from the transmit antenna to the receive antenna at the relay [14]. Also, the relay is assumed to have no other energy supply but only the energy harvested from the source [15].

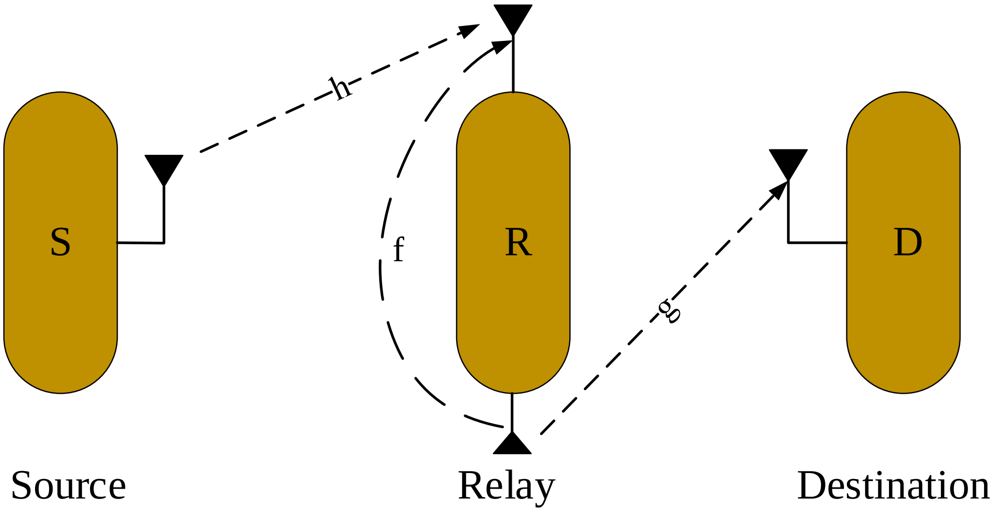

Fig. 1. Dual-hop full-duplex relay networks model

For separating between information transferring and energy harvesting processes at relay node, we adopt the time-switching relaying protocol (TSR) [6]. Here, the total symbol duration T is divided into two intervals with the lengths of αT and $(1-\alpha)T$, respectively. The first interval corresponds to the energy harvesting phase and the second one corresponds to the information transmission phase. **Fig. 2** explains the TSR protocol visually. During the energy harvesting period, the second antenna of relay node is free from transmission duty and can be exploited to harvest energy from the source [9].

Regarding to the channel model, we consider the case that the channel state information is obtained with error. The effect of CSI error on the performance of the model of interest is the main concentration of this paper. Let h and g denote the channels from the source to the relay and from the relay to the destination, respectively, and let f denote the loopback interference channel at the relay. We assume that all channels experience Rayleigh fading and keep constant during each transmission block (flat fading). Specifically, $|h|^2$ is an exponential random variable with mean λ_h, $|g|^2$ is exponentially distributed with mean λ_g, and $|\hat{f}|^2$ is exponentially distributed with mean λ_r, which is a key parameter related to the strength of the loopback interference. Due to imperfect channel estimation, the estimated channel gains obtained at the relay and the destination are expressed as

$$\begin{cases} \hat{h} = h + \Delta h \\ \hat{g} = g + \Delta g \\ \hat{f} = f + \Delta f \end{cases} \tag{1}$$

where $\Delta h, \Delta g$, and Δf are the channel estimation error corresponding to *h*, *g*, and *f*, respectively. These estimation errors are all assumed to be Gaussian distributed with zero mean.

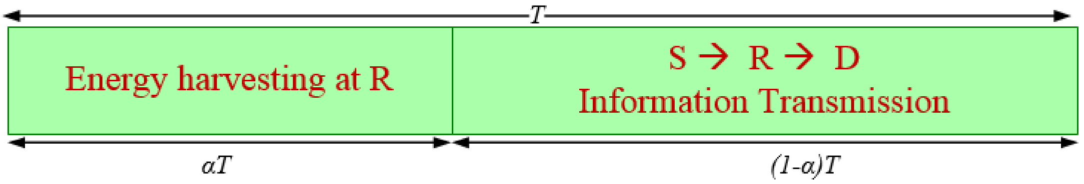

Fig. 2. TSR protocol for energy harvesting

2.1 Energy harvesting phase

As mentioned above, during the energy harvesting phase, the second antenna of the relay can be exploited to enhance the energy capturing process. In [10], the authors confirm that at high SINR regime, there is no significant difference in performance when adding this extra antenna. Hence, we only consider the case that only the information receiving antenna is used to collect energy.

During the energy harvesting phase, the received signal at the relay node can be expressed as

$$y_r = hx_e + n_r \tag{2}$$

where h is the channel coefficient of the first antenna, x_e is the energy symbol with $E|x_e|^2 = P_s$, where $E[X]$ denotes the expectation operation. n_r is the zero mean additive white Gaussian noise (AWGN) with variance N_0. Hence, the energy harvested during this phase can be computed as

$$E_n = \eta P_s(|\hat{h}|^2 + \delta_{\Delta h}^2)\alpha T \tag{3}$$

The relay transmit power can be computed as [16]

$$P_R = \frac{\eta P_S(|\hat{h}|^2 + \delta_{\Delta h}^2)\alpha T}{(1-\alpha)T} = kP_S(|\hat{h}|^2 + \delta_{\Delta h}^2) \tag{4}$$

where η is a constant and denotes the energy conversion efficiency, k is defined as $k \triangleq \frac{\eta\alpha}{1-\alpha}$, and $\delta_{\Delta h}^2$ is the standard deviation of the channel estimation error Δh, which is a zero-mean Gaussian random variable as mentioned above.

2.2 Information transmission phase

Now we consider the information transmission phase. Here, the received signal at the relay is given by

$$y_R = hx_s + fx_R + n_r \tag{5}$$

where x_s is the transmitted signal, which satisfies $E|x_s|^2 = P_s$, x_r is the loopback interference due to full-duplex relaying and satisfies $E|x_r|^2 = P_r$, f denotes the loopback interference channel, and n_r is the zero mean AWGN with variance N_0. After applying interference cancellation methods to mitigate the loopback interference [14], the received signal at the relay is determined by

$$\begin{aligned}\hat{y}_R &= y_R - \hat{f}\, x_R \\ &= (\hat{h} + \Delta h)x_s + \Delta f x_R + n_r\end{aligned} \tag{6}$$

In our model, amplify-and-forward protocol is used, hence, the received signal at relay is amplified by a factor γ which is given by [14]

$$\gamma^2 = \frac{P_R}{(\left|\hat{h}\right|^2 + \delta_{\Delta h}^2)P_s + \delta_{\Delta f}^2 P_R + N_0} \tag{7}$$

At destination, the following signal is received:

$$\begin{aligned}y_d &= (\hat{g} + \Delta g)x_R + n_d \\ &= \hat{g}\gamma\left\{(\hat{h} + \Delta h)x_s + \Delta f x_R + n_r\right\} + \Delta g \gamma \left\{(\hat{h} + \Delta h)x_s + \Delta f x_R + n_r\right\} + n_d\end{aligned} \tag{8}$$

3. Performance Analysis

In this section, we proceed to analyze the throughput performance of FD relaying with RF energy harvesting using a single antenna. The dependence of system throughput on the time-switching factor is derived and the optimal time allocation is found. Here, we consider the instantaneous transmission mode.

3.1 Outage probability and system throughput

First, we consider the instantaneous throughput of the system. For the AF protocol, the end-to-end SINR can be expressed as

$$SINR = \frac{A}{B} \tag{9}$$

where

$$A = \left|\hat{g}\right|^2 \left|\hat{h}\right|^2 P_S P_R \tag{10}$$

and

$$\begin{aligned}B = {} & P_s P_R \delta_{\Delta h}^2 \left|\hat{g}\right|^2 + P_R^2 \left|g\right|^2 \delta_{\Delta f}^2 + \left|g\right|^2 P_R N_0 + P_s P_R \delta_{\Delta g}^2 \left|\hat{h}\right|^2 + P_s P_R \delta_{\Delta g}^2 \delta_{\Delta h}^2 \\ & + \delta_{\Delta g}^2 P_R^2 \delta_{\Delta f}^2 + P_R \delta_{\Delta g}^2 N_0 + P_s \left|\hat{h}\right|^2 N_0 + P_R \delta_{\Delta f}^2 N_0 + N_0^2 + P_s \delta_{\Delta h}^2 N_0\end{aligned} \tag{11}$$

We divide both numerator and denominator of (9) by P_R and substitute (4) into (9). After doing some algebra, we obtain

$$SINR = \frac{C}{D} \tag{12}$$

where

$$C = \left|\hat{g}\right|^2 \left|\hat{h}\right|^2 P_S \tag{13}$$

$$D = P_s \delta_{\Delta h}^2 \left|\hat{g}\right|^2 + P_R \left|g\right|^2 \delta_{\Delta f}^2 + \left|g\right|^2 N_0 + P_s \delta_{\Delta g}^2 \left|\hat{h}\right|^2 + P_s \delta_{\Delta g}^2 \delta_{\Delta h}^2 + \delta_{\Delta g}^2 P_R \delta_{\Delta f}^2$$

$$+\delta_{\Delta g}^{2} N_0 + \frac{N_0}{k} + \delta_{\Delta f}^{2} N_0 \tag{14}$$

Assume that the source transmits at a constant rate R. Let $z = 2^R - 1$ be the lower threshold for SINR. Here, the average throughput can be computed as [6]

$$R_{DL}(\alpha) = (1 - P_{out}) R (1-\alpha) \tag{15}$$

where P_{out} is the outage probability. Hence, the optimal time-switching factor α could be obtained by solving the following optimization problem

$$\alpha^{*} = \arg\max_{\alpha} R_{DL}(\alpha) \tag{16}$$

One of the main contributions of this paper is the analysis of outage performance of the proposed system in the condition of imperfect CSI. Our analytical result is stated in the following proposition.

Proposition 1

For the AF protocol, the outage probability and the average throughput of the system can be expressed as

$$P_{out} = 1 - \frac{e^{\left(\frac{-b_2}{b_1\lambda_h} - \frac{a_1}{b_1\lambda_g}\right)}}{\lambda_h b_1} \sqrt{4Vb_1\lambda_h}\, K_1\left(\sqrt{\frac{4V}{b_1\lambda_h}}\right) \tag{17}$$

and

$$R_{DL}(\alpha) = R(1-\alpha) \frac{e^{\left(\frac{-b_2}{b_1\lambda_h} - \frac{a_1}{b_1\lambda_g}\right)}}{\lambda_h b_1} \sqrt{4Vb_1\lambda_h}\, K_1\left(\sqrt{\frac{4V}{b_1\lambda_h}}\right) \tag{18}$$

where $K_n(x)$ *is the n*th *order modified Bessel function of the second kind and*

$$V = \frac{a_1 b_2 + a_2 b_1}{b_1 \lambda_g}$$

where a_1, a_2, b_1, b_2 *are determined in the following equations*

$$a_1 = z(\delta_{\Delta g}^{2} P_s + \delta_{\Delta g}^{2} \delta_{\Delta f}^{2} k P_s) \tag{19}$$

$$a_2 = z(\delta_{\Delta g}^{2} \delta_{\Delta f}^{2} \delta_{\Delta h}^{2} k P_s + \delta_{\Delta g}^{2} N_0 + \frac{N_0}{k} + \delta_{\Delta f}^{2} N_0) \tag{20}$$

$$b_1 = P_s - k P_s \delta_{\Delta f}^{2} z \tag{21}$$

$$b_2 = z(P_s \delta_{\Delta h}^{2} + k P_s \delta_{\Delta f}^{2} \delta_{\Delta h}^{2} + N_0) \tag{22}$$

Proof. The outage probability of our system is given by

$$P_{out} = Pr\{SINR \le (2^R - 1)\} \tag{23}$$

Let $x = |\hat{g}|^2$ and $y = |\hat{h}|^2$. Equation (23) can be rewritten as

$$P_{out} = P\left(x \le \frac{y a_1 + a_2}{y b_1 - b_2} \right) \tag{24}$$

where a_1, a_2, b_1, b_2 are given by equations (19) - (22).

Now, the outage probability can be computed as [6]

$$P_{out} = 1 - \frac{1}{\lambda_h} \int_{y=b2/b1}^{\infty} e^{-\left(\frac{y}{\lambda_h} + \frac{y a_1 + a_2}{(y b_1 - b_2)\lambda_g} \right)} dy \tag{25}$$

Let $u = y b_1 - b_2$, then by changing variable in (25), we obtain

$$P_{out} = 1 - \frac{e^{\left(\frac{-b_2}{b_1 \lambda_h} - \frac{a_1}{b_1 \lambda_g} \right)}}{\lambda_h b_1} \int_0^{\infty} e^{\left(-\frac{V}{u} - \frac{u}{\lambda_h b_1} \right)} du \tag{26}$$

After doing some reduction and apply the integral formula 3.324.1 in [17], we get the following formula

$$P_{out} = 1 - \frac{e^{\left(\frac{-b_2}{b_1 \lambda_h} - \frac{a_1}{b_1 \lambda_g} \right)}}{\lambda_h b_1} \sqrt{4 V b_1 \lambda_h} K_1 \left(\sqrt{\frac{4V}{b_1 \lambda_h}} \right)$$

3.2 Optimal time switching factor

The optimal value α^* can be obtained by solving the equation $\frac{dP_{out}(\alpha)}{d\alpha} = 0$. Given the outage expression in (17), this optimization problem does not admit a closed-form solution. However, the optimal α is efficiently solved via numerical calculation, as illustrated below.

Here, we can use Golden section search algorithm to find the optimal factor α^*. This algorithm has been used in many global optimization problems in communications, for example, in [18]. The detailed algorithm as well as the related theory is described in [19].

3.3 Asymptotic analysis

In (17) and (18), the outage probability and average system throughput are expressed in terms of the first order modified Bessel function of the second kind, which can be approximated to a simpler expression in high SINR regime. Hence, our next objective is to derive the asymptotic behavior of the outage probability and average throughput of the proposed system when the transmitted power P_s from the source goes to infinity.

Proposition 2

At high SINR regime, i.e. when the transmitted power P_s goes to infinity, the outage probability P_{out} can be approximated by the following expression:

$$P_{out} = 1 - e^{-zb\delta^2}\sqrt{\frac{4\delta_{\Delta h}^2\delta_{\Delta g}^2 I}{\lambda_h\lambda_g}}K_1\left(\sqrt{\frac{4\delta_{\Delta h}^2\delta_{\Delta g}^2 I}{\lambda_h\lambda_g}}\right) \tag{27}$$

where b, δ^2, and I are given by

$$b = \frac{1+k\delta_{\Delta f}^2}{1-zk\delta_{\Delta f}^2} \tag{28}$$

$$\delta^2 = \frac{\delta_{\Delta h}^2}{\lambda_h} + \frac{\delta_{\Delta g}^2}{\lambda_g} \tag{29}$$

$$I = z^2 b^2 + \frac{zk\delta_{\Delta f}^2}{1-zk\delta_{\Delta f}^2} \tag{30}$$

Proof. Equation (17) can be rewritten as

$$P_{out} = 1 - e^{\left(\frac{-b_2}{b_1\lambda_h} - \frac{a_1}{b_1\lambda_g}\right)} \cdot \sqrt{\frac{4V}{b_1\lambda_h}}K_1\left(\sqrt{\frac{4V}{b_1\lambda_h}}\right) \tag{31}$$

As P_s goes to infinity, the rational terms in (31) converge to the following quantities:

$$\begin{aligned}\lim_{P_s\to\infty}\left(\frac{-b_2}{b_1\lambda_h} - \frac{a_1}{b_1\lambda_g}\right) &= -\frac{z\delta_{\Delta h}^2 + zk\delta_{\Delta h}^2\delta_{\Delta f}^2}{\left(1-zk\delta_{\Delta f}^2\right)\lambda_h} - \frac{z\delta_{\Delta g}^2 + zk\delta_{\Delta g}^2\delta_{\Delta f}^2}{\left(1-zk\delta_{\Delta f}^2\right)\lambda_g} \\ &= -\frac{z\delta_{\Delta h}^2(1+k\delta_{\Delta f}^2)}{\left(1-zk\delta_{\Delta f}^2\right)\lambda_h} - \frac{z\delta_{\Delta g}^2(1+k\delta_{\Delta f}^2)}{\left(1-zk\delta_{\Delta f}^2\right)\lambda_g} = -zb\delta^2\end{aligned}$$

and

$$\begin{aligned}\lim_{P_s\to\infty}\left(\frac{4V}{b_1\lambda_h}\right) &= \lim_{P_s\to\infty}\left(4\frac{a_1b_2 + a_2b_1}{b_1^2\lambda_g\lambda_h}\right) = \lim_{P_s\to\infty}\frac{4}{\lambda_g\lambda_h}\left(\frac{a_1b_2}{b_1^2} + \frac{a_2}{b_1}\right) \\ &= \frac{4}{\lambda_g\lambda_h}\left(\frac{z(\delta_{\Delta g}^2 + \delta_{\Delta g}^2\delta_{\Delta f}^2 k)z(\delta_{\Delta h}^2 + k\delta_{\Delta f}^2\delta_{\Delta h}^2)}{(1-k\delta_{\Delta f}^2 z)^2} + \frac{z\delta_{\Delta g}^2\delta_{\Delta f}^2\delta_{\Delta h}^2 k}{1-k\delta_{\Delta f}^2 z}\right) \\ &= \frac{4\delta_{\Delta g}^2\delta_{\Delta h}^2}{\lambda_g\lambda_h}\left(z^2b^2 + \frac{z\delta_{\Delta f}^2 k}{1-zk\delta_{\Delta f}^2}\right)\end{aligned}$$

By the continuity of P_{out} with respect to P_s, we obtain the desired results.

4. Numerical Results

In this section, numerical simulation is conducted to verify the analytical results developed in the previous section. We consider a network with one source, one relay, and one destination, where source-relay and relay-destination distances are both normalized to unit value. Other simulation parameters are listed in **Table 1**.

Table 1. Simulation parameters

Symbol	Name	Values
R	Source rate	3bps/Hz
z	SINR threshold	7
η	Energy harvesting efficiency	1
λ_h	Mean of $\lvert h\rvert^2$	1
λ_g	Mean of $\lvert g\rvert^2$	1
N_0	Noise variance	1

Fig. 3 and **Fig. 4** shows the achievable rate and outage probability of the system versus the transmitted power P_s in 2 cases: perfect CSI and imperfect CSI with all of the standard deviation of channel estimation errors are equal to $\delta_0 = 0.1$. The time-switching factor α is set to 0.3. It's can be observed that the simulation curve and the analytical curve almost overlap together.

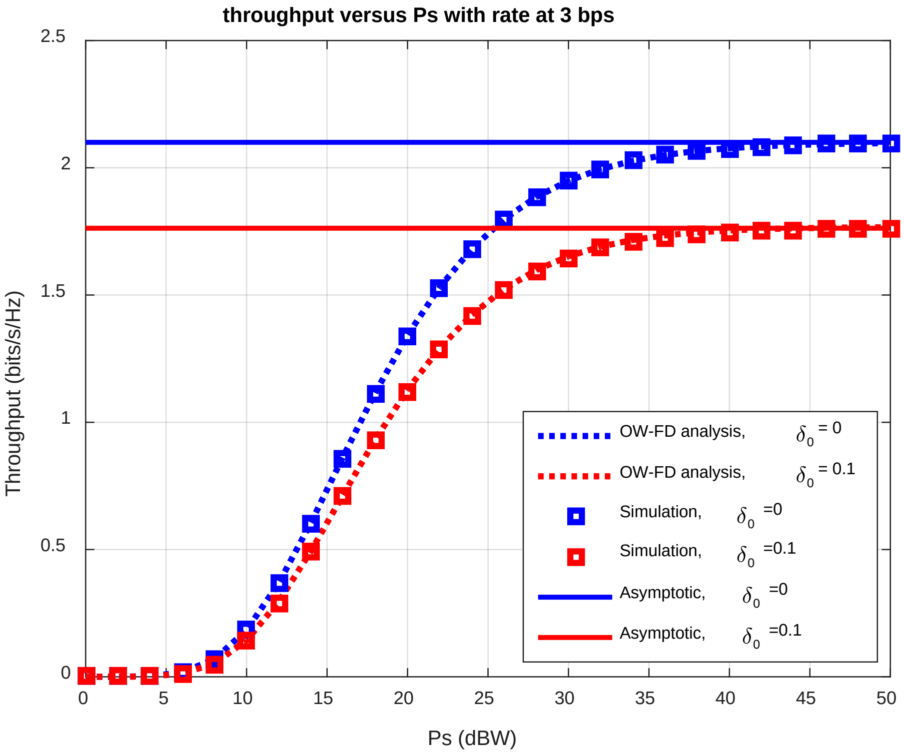

Fig. 3. System throughput versus source transmitted power

This confirms our mathematical analysis in the previous section. We also notice that in the low SINR regime, the channel estimation error has little effect on system performance. However, when the transmit power goes large, the channel estimation error has increasing impact on both achievable throughput as well as outage probability.

The asymptotic behavior of the outage probability and system throughput when SINR goes to infinity is also illustrated in **Fig. 3** and **Fig. 4**. The solid blue lines and red lines in both figures indicate the asymptotic performance of the proposed system in cases of perfect and imperfect CSI, respectively.

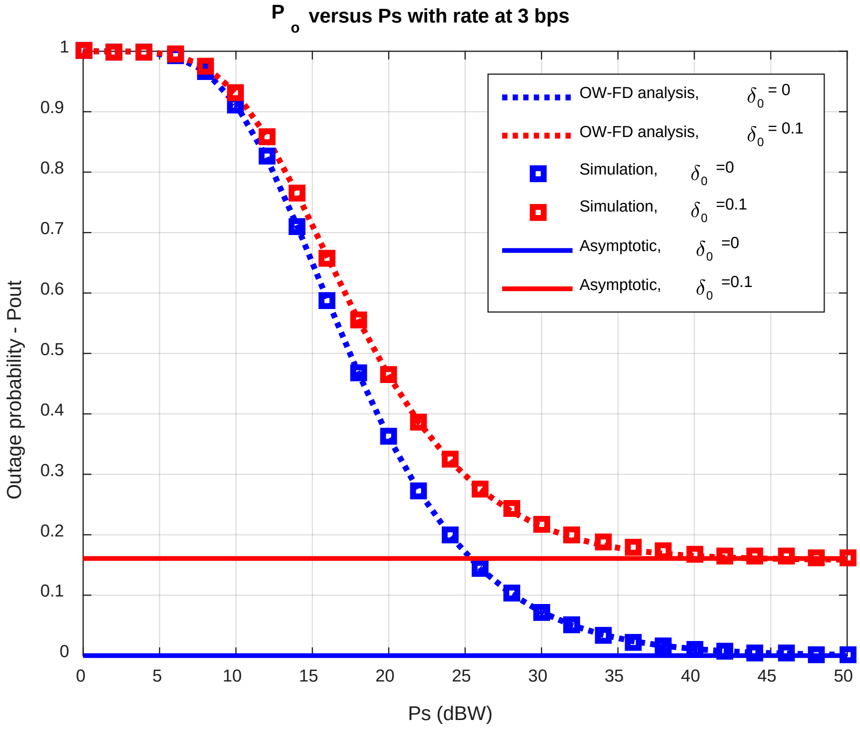

Fig. 4. Outage probability versus source transmitted power

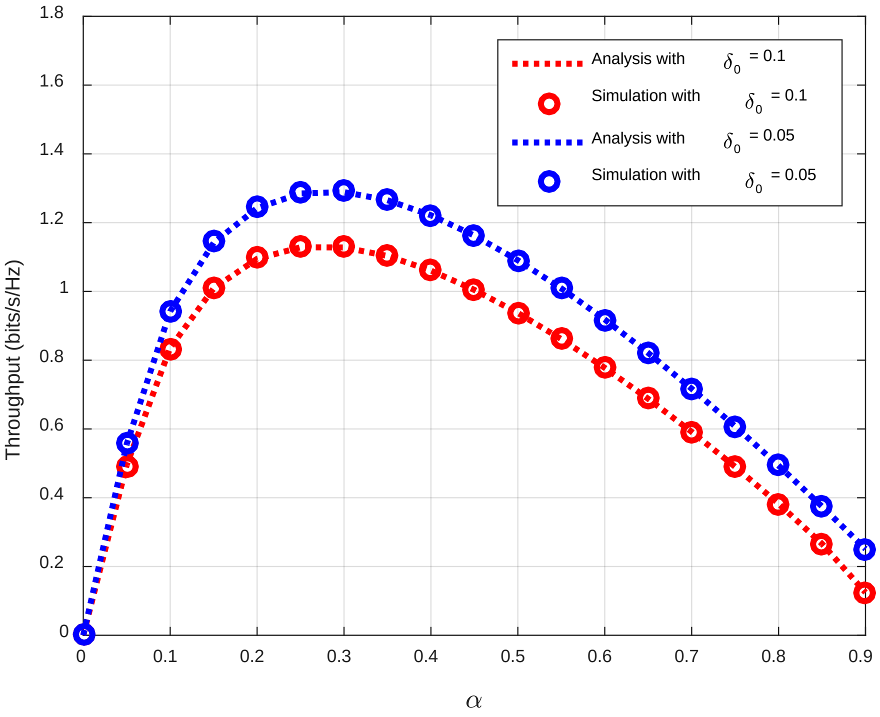

Fig. 5. System throughput versus time switching factor

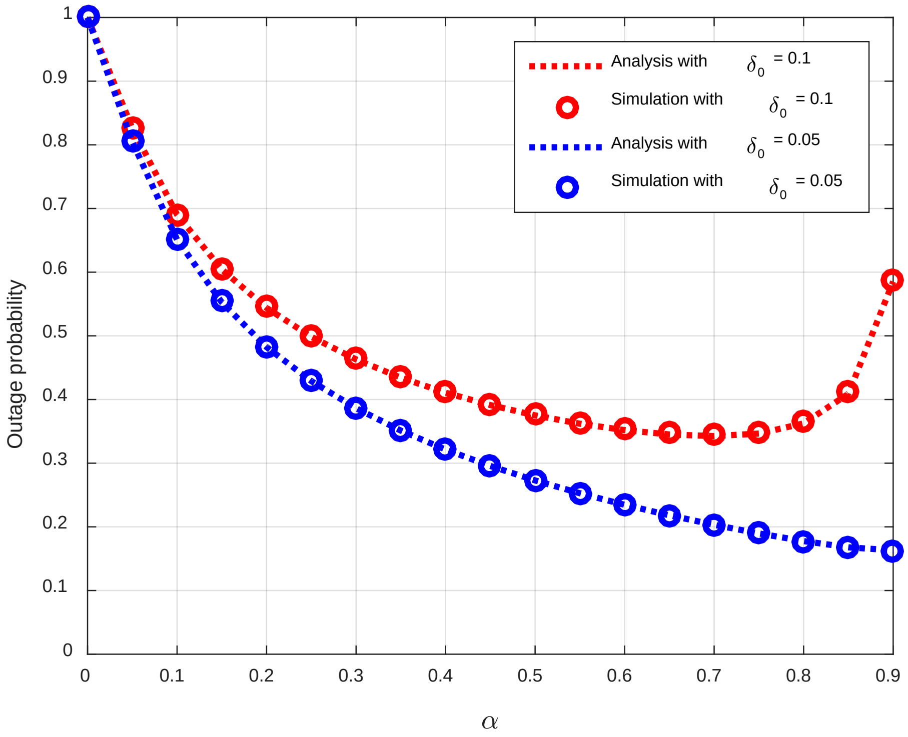

Fig. 6. Outage probability versus time switching factor

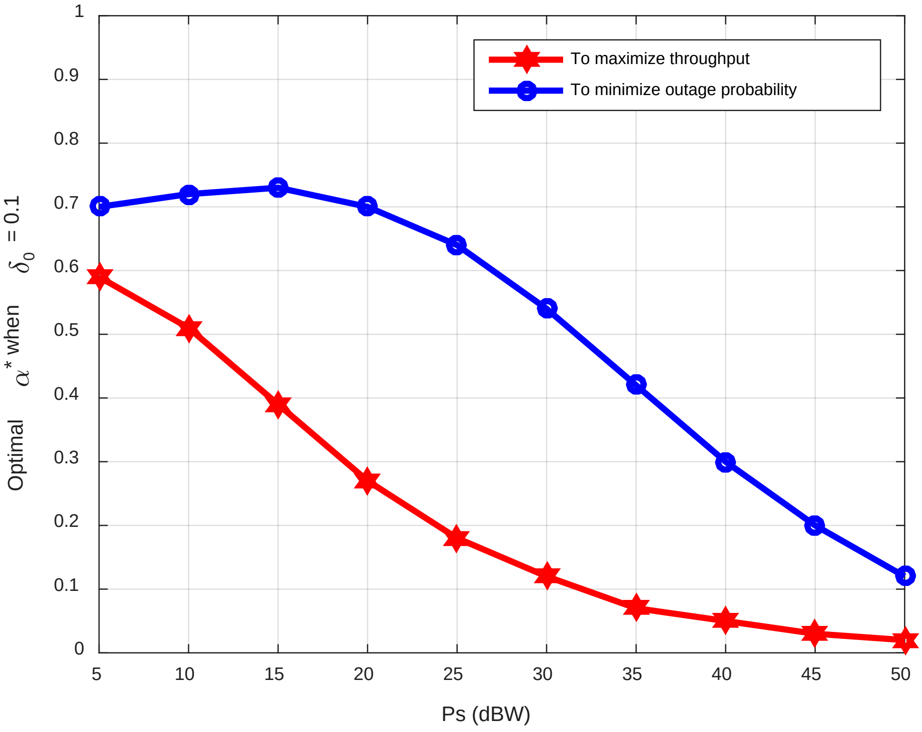

Fig. 7. Optimal time switching factor versus transmitted power

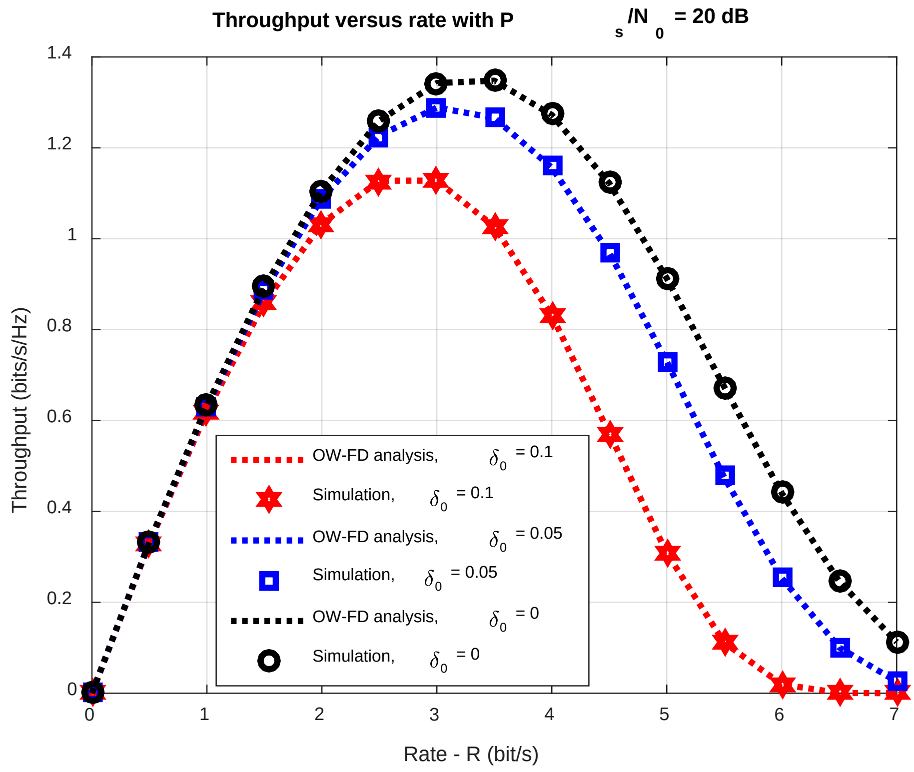

Fig. 8. System throughput versus source transmitted rate

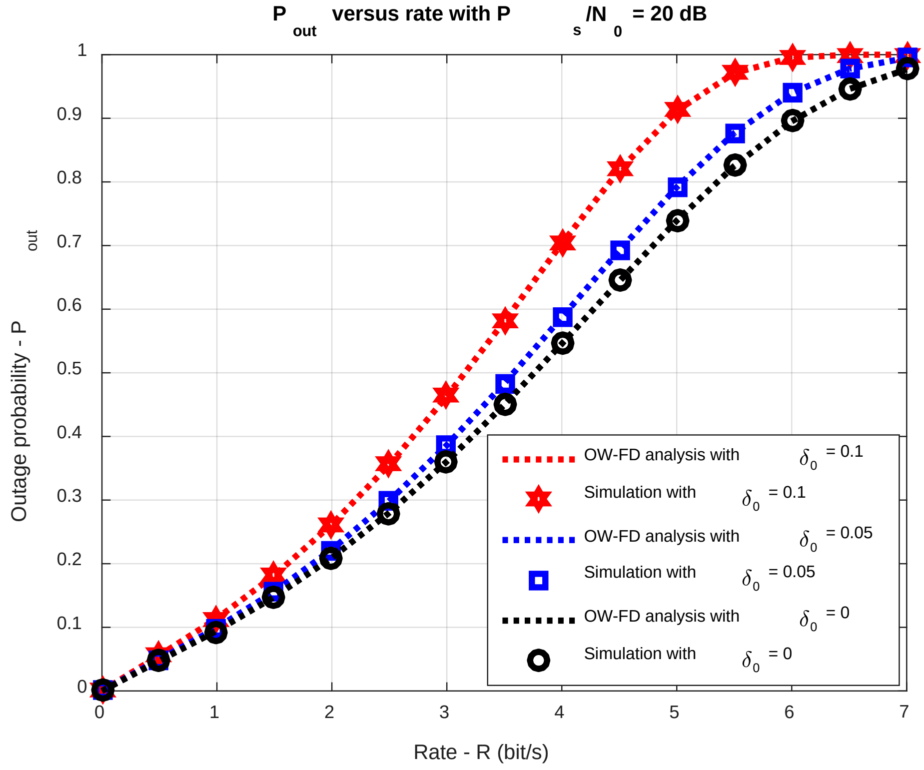

Fig. 9. Outage probability versus source transmitted rate

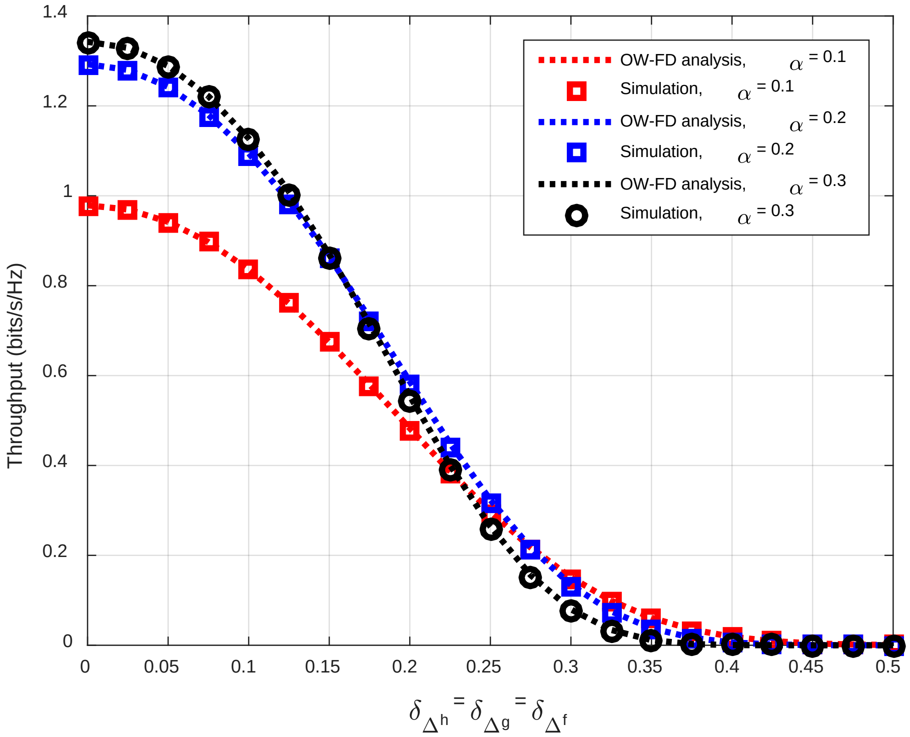

Fig. 10. System throughput versus channel estimation error

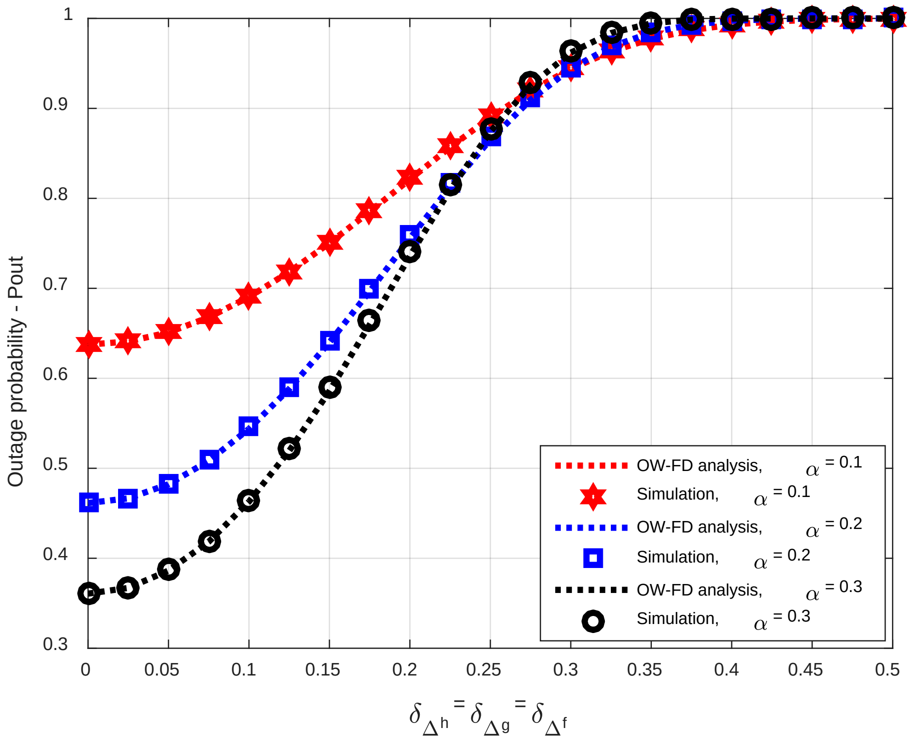

Fig. 11. Outage probability versus channel estimation error

The impact of time switching factor α on the instantaneous capacity is shown in **Fig. 5**. Here, the transmitted power is set to 20dBW. Again, the analytical solutions are in exact agreement with the simulation results. There exists a unique time switching factor at which the system throughput is maximized. In practice, this optimal factor can be found iteratively using numerical methods.

The outage probability also depends on the time switching factor α, which is illustrated in **Fig. 6**. Similar to the throughput performance, the outage probability can be minimized with an appropriate selection of α. However, the optimal α^* for outage performance is different from the optimal α^* for system throughput.

The optimal time switching factor α^* can be found by using the Golden section search (GSS) algorithm as mentioned in Section 3.2. **Fig. 7** shows the values of optimal switching factor α^* according to different values of P_s while $\delta_{\Delta h} = \delta_{\Delta g} = \delta_{\Delta f} = 0.1$.

Fig. 8 and **Fig. 9** examine the impact of transmission rate R_c on the throughput and outage probability of considered systems with $\alpha = 0.3$ and $P_s / N_0 = 20dB$. As in the case of perfect CSI [10], the throughput first increases with the transmission rate R, and then decreases when R increases beyond the rate value of $3bps/Hz$. In other words, for a particular transmit power, there exists a unique transmission rate which yields maximum throughput. Regarding the outage probability, **Fig. 9** confirms that it increases when the transmission rate increases, i.e., there is a performance trade-off between the transmission rate and the outage probability of the system.

Fig. 10 and **Fig. 11** illustrate the impact of the channel estimation error on the throughput and outage probability of our system, respectively. Again, we set $P_s / N_0 = 20dB$ in this simulation. As we intuitively expected, the throughput decreases and the outage probability increases when the standard deviation of channel estimation error increases. In fact, the system performance degrades significantly after the error exceeds certain threshold value (around 0.1 in this simulation scenario). From both figures, we can confirm that if we can keep the error bounded in some narrow interval, then the throughput and outage capacity are still close to ones in the case of perfect CSI.

5. Conclusion

In this paper, we have studied the throughput and outage probability of dual-hop FD relay networks using RF energy harvesting with time-switching protocol. Different from previous studies on RF energy harvesting in relay networks, this work emphasizes on the impact of channel estimation error on the system performance. Based on the assumption that the channel estimation error is zero-mean Gaussian distributed, we derive the analytical formula for outage probability and ergodic capacity of the system as well as their asymptotic behavior at high SINR regime, and validate these results by numerical analysis as well. An algorithm to determine the optimal time switching factor is also introduced. From the numerical results, it can be observed that the channel estimation error has little impact on the system performance at low SINR regime, and more impact at high SINR regime. However, even at high SINR regime, the system performance can still be good if the channel estimation error is bounded in some interval, which is not impossible in practice with advanced channel estimation techniques.

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